

# Assessing Potential Earthquake Loss in Mérida State, Venezuela Using Hazus

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**Abstract** The focus of the Hazus earthquake model has been largely U.S. centric due to a lack of standardized building-infrastructure data formats applicable elsewhere. In a combined effort between FEMA Region VIII and the Universidad de Los Andes, Venezuela, the present study uses the Hazus 2.1 software to simulate earthquake loss estimations for Venezuela. Population totals and demographic distributions were developed using Oak Ridge National Labs Landscan 2008 population data and the census 2011 for Venezuela. The accuracy of the model was further enhanced for Mérida State, located in western Venezuela, by collecting, incorporating, and developing region and specific inventories including soil maps, liquefaction and landslide susceptibility studies, demographic data, and building inventory information. We used USGS ShakeMaps scenarios for two potential earthquake events with peak ground accelerations proposed within Performance Based Seismic Engineering of Buildings, VISION 2000 recommendations. The region has not witnessed an earthquake with a magnitude greater than M 7 in the last 120 years. Given the historical record of seismicity and the seismotectonics in the region, it becomes increasingly important to understand the potential implications from moderate to large earthquakes in Mérida State, Venezuela.

**Keywords** Disaster loss estimation · Earthquake damage Hazus · Seismic risk · Venezuela

## 1 Introduction

Earthquake disasters result in severe devastation and cause deaths to a large number of people every year. Deaths and destruction due to earthquakes can be reduced with the application of mitigation principles, especially through adoption and enforcement of building codes and targeted investments. Managing risk will become a more urgent and demanding task in the coming years, mainly because vulnerabilities are rapidly increasing as a result of population growth and the inability to incorporate earthquake mitigation strategies. Mechanisms for reducing risk need to be more agile and effective at all levels and scales of government, as well as in people's daily lives.

An important objective of this study is to highlight that another large earthquake is a potential reality in Mérida State at any time; however, the day this event may occur cannot be predicted. Future impacts are likely to have more severe losses than the last large earthquake, due to the fact that the total population has grown from 4,500 since the last earthquake on 28 April 1894 to about 800,000 (INE 2011). Currently 88 % of the region's population lives in urban areas characterized by vulnerable building types. In order to be prepared for such a natural hazard, we must be able to estimate the potential losses associated with various scenarios and thus be in a better position to develop a mitigation plan. Seismic risk and loss maps are used in a number of ways to increase general public awareness of earthquake hazard, carry out urban planning, select sites for important facilities (for example, hospitals and schools), provide a basis for whether site-specific hazard evaluations should be performed, aid emergency preparedness and response, and estimation potential loss (Wong 2010). By implementing Hazus, we are able to communicate this risk in terms of potential loss of life and property as well as

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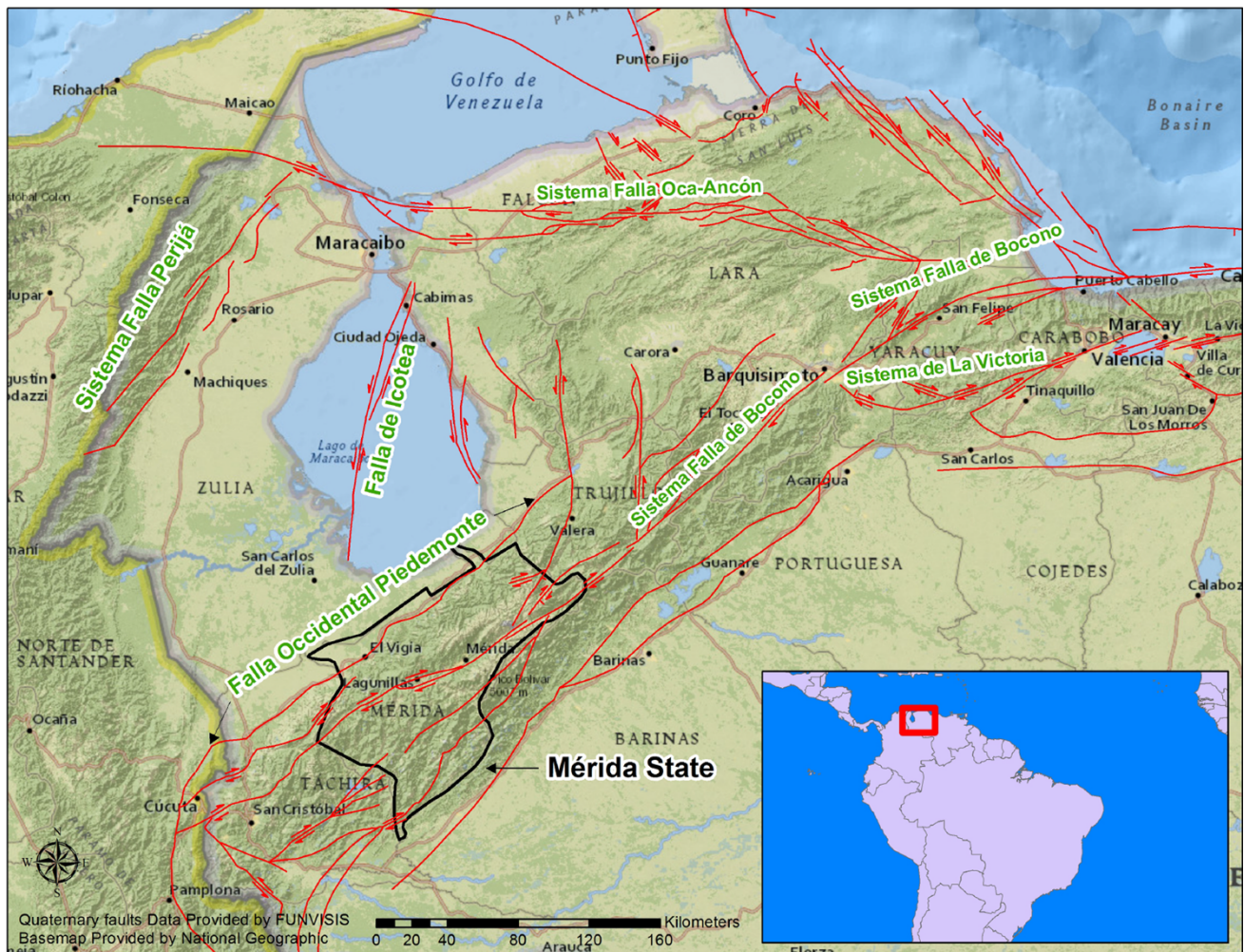
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economic impacts; it is also possible to make risk management decisions that include prioritizing mitigation strategies. We believe this study is important to engineers, architects, and policymakers at all levels (local, regional, and national), insurance companies, emergency managers, and business owners. As a result of this study, we have successfully engaged local policymakers involved in seismic risk reduction in Mérida State.

Bendito et al. (2001) conducted the Probabilistic Seismic Hazard Analysis (PSHA) for the western Venezuela region (Fig. 1), which provided important inputs for our scenario selection exercise. We chose two scenario earthquakes that: (1) mainly adhere to the general guidelines proposed by the Structural Engineers Association of California's VISION 2000 Committee in *Performance Based Seismic Engineering of Buildings* (SEAOC Vision 2000 Committee 1995); (2) are similar to earthquakes within the recorded historical earthquake record in the region; and (3) assume that such

scenario earthquakes could potentially generate ground motions inside our study region that correspond to return periods of 475 and 970 years, respectively. These return periods are an important assumption of the present study, which could have been easily reconfirmed or validated if rigorous seismic disaggregation analyses were available for the study region.

To estimate seismic loss potentials from scenario earthquakes this study utilized Hazus earthquake loss estimation technology. Hazus is a comprehensive, GIS-based modeling framework developed by the Federal Emergency Management Agency (FEMA) in partnership with the National Institute of Building Sciences (NIBS). The earthquake hazard in the Hazus model may be derived from a deterministic event, a probabilistic analysis of seismic hazard, or a user-supplied map of ground motion. The Hazus user-supplied map interface, with ShakeMaps generated by U.S. Geological Survey (USGS 2009), were used for this study.



**Fig. 1** Neotectonic map of western Venezuela, showing quaternary faults. Source data and map reused with permission of FUNVISIS and National Geographic

Our model incorporates detailed data on the building inventory using a database of about 375,000 buildings. The data base includes building age, size, location, number of stories, and structural typology, as well as population demography and distribution, the history of earthquakes in the region, and potential soil amplification, landslide, and liquefaction susceptibility. By using these data sets interactively, we can identify and map the areas of greater vulnerability and the structures with the highest risk.

## 2 Mérida State and Its Earthquake Potential

Venezuela is a country located in the northern part of South America, open to the Caribbean Sea through its northern flank, with Brazil to the south, English Guyana to the east, and Colombia to the west. Venezuela has a surface area of 912,050 km<sup>2</sup>, divided into six natural regions with geographical variety and differences between the geologic formations that compose it. Mérida State is located on an elongated plateau inside a valley within the Andean region in western Venezuela (Fig. 1). This plateau is oriented southwest-northeast surrounded by two mountain chains: the Sierra Nevada (southeast) and the Sierra de la Culata (northwest). The Chama and Albarregas Rivers flow through the tableland (Castillo 2006).

Since the pioneering work of Rod (1956), the Boconó fault is acknowledged as the most active tectonic feature in the Venezuelan Andes region with a significant seismogenic capacity. The Boconó fault trends northeast-southwest over a distance of about 600 km from the Táchira depression to the town of Morón, Carabobo on the Caribbean coast (Fig. 1). The fault extends along the Venezuelan Andes slightly oblique to its longitudinal axis and displays right-lateral kinematic motion with an average slip rate of 9–10 mm/a in the Apartaderos Town (northeast Mérida State). This major tectonic structure has been divided into five segments based essentially on geometric criteria that utilizes data from 11 paleoseismic trenches, which confirmed that the geometric segments were also likely seismogenic segments (Laffaille et al. 2010).

In the western region of Venezuela, large earthquakes have occurred. One of the most destructive occurred on 26 March 1812, with an estimated magnitude of M 7.3. This is one of the more catastrophic seismic events in Venezuela's history because it caused damages and casualties in the entire country and had destructive effects in Saint Vincent and Jamaica. Caracas, at the time a city of 32,000 inhabitants and the capital of Venezuela, was reduced to ruins, and most of the churches were completely destroyed. La Guaira, Maiquetia, Mérida, and San Felipe suffered the same fate (Laffaille et al. 2010). The last large earthquake occurred on 28 April 1894 in the central longitudinal valley

between Mérida City and Bailadores Town (southwest Mérida State), with a magnitude of M 7.1 and a death toll of 345 people.

The seismic hazard map of Venezuelan seismic design codes for buildings (COVENIN 1756:2001) divides the country into seven zones; the hazard in these zones ranges from very high to low. Design peak ground acceleration varies from 0.40 g in zone 7–0.10 g in zone 1 at rock sites, associated with a probability of exceedance of 10 % in 50 years. Mérida State is placed in seismic zone 5 as a high seismic zone that is also consistent with the global hazard map developed by the Global Seismic Hazard Assessment Program (GSHAP 1999).

## 3 Methodology

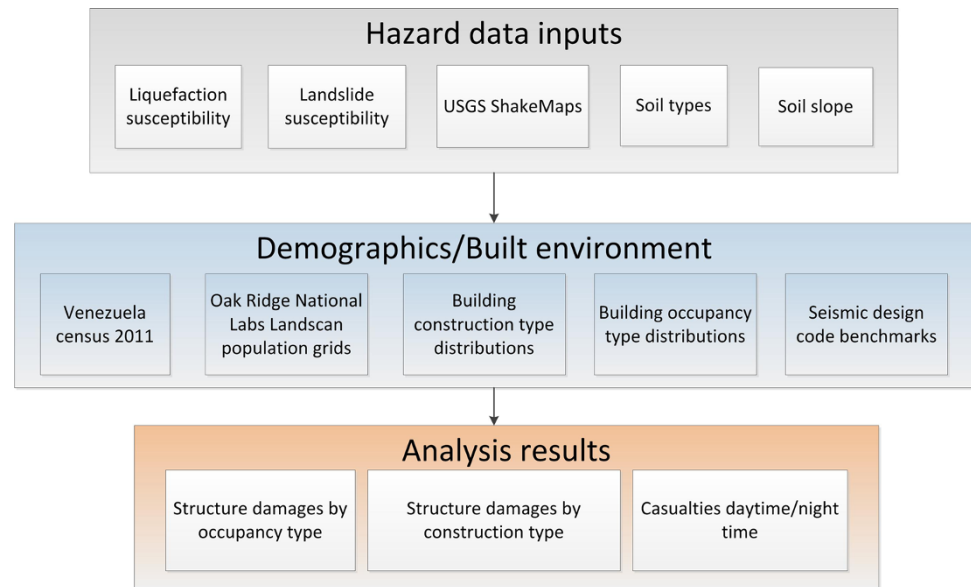
To estimate seismic loss potentials from scenarios earthquakes in Mérida State, this study utilized Hazus MH 2.1 (NIBS 2012) earthquake loss estimation technology. Hazus is a GIS-based desktop application used for comprehensive seismic risk assessment modeling. This tool allows an engineering approach to modeling of infrastructure and helps in quantifying consequences to interdependent systems and sectors. The technology was developed by FEMA in partnership with the National Institute of Building Sciences (NIBS). The first version of Hazus was made only for earthquake loss estimation. Recent versions of Hazus were extended to multihazard loss estimation and also include hurricane and flood loss estimation capabilities. Government agencies and researchers use Hazus for mitigation, emergency preparedness, and disaster response.

The software was adopted successfully in several states in the United States (for example, Buika 2000; Kircher et al. 2006a; Tantala et al. 2008; Rein and Corotis 2013) and it is continually tested using U.S. as well as international earthquakes (Kircher 2003; Chock et al. 2006; Remo and Pinter 2012). Hazus is also used in several other countries (for example, Gulati 2006; Korkmaz 2009; Ploeger et al. 2010; Nastev 2013; Levi et al. 2014). The goal of providing Hazus functionality outside the USA is that it allows international users to concentrate efforts on data development using an existing methodology rather than invest significant time and resources into software development.

This study is an advanced application of Hazus (Level II), since we incorporate user-supplied ground motions through the USGS ShakeMap program, additional hazard information concerning landslide and liquefaction susceptibility, and a custom building inventory including attributes necessary for loss estimation (year built, estimated floor area, number of stories, and location) of 375,029 buildings for the study area and 5.4 million for the nation.



**Fig. 2** Modules of FEMA/Universidad de Los Andes Hazus methodology



A conceptual view of how this information was pulled together and applied to this study is shown in Fig. 2. The advantage of a modular methodology is that it enables users to limit their studies to selected losses. For example, for this study, we concentrated our efforts on the direct physical damage to building stock in order to estimate building damage, losses, and potential casualties related to building and occupancy types.

In Hazus, building stock is classified both in terms of use, or occupancy class, and structural system, or model building type. Twenty-eight occupancy classes define residential, commercial, industrial, or other building occupancies and 36 model-building types define structural systems of wood, steel, concrete, masonry materials, and mobile homes. The building damage functions distinguish among buildings that are designed to different seismic standards or are otherwise expected to perform differently during an earthquake. Damage functions are provided for four seismic designs levels, categorized as High-Code (H), Moderate-Code (M), and Low-Code (L), and an additional design category for Pre-Code buildings. The Pre-Code design category includes buildings built before seismic codes were required for building design (Kircher et al. 2006b). This represents U.S. buildings generally built before 1940 or where the seismic threat was not recognized. These 36 types at 4 design levels amounts to 144 Hazus building damage functions that have two basic components: capacity curves and fragility curves. The capacity curves are based on engineering parameters of structural strength that characterize the nonlinear pushover structural behavior of the 36 types of model buildings. The fragility curves describe the probability of reaching or

exceeding discrete states of damage for the structure and nonstructural systems. The states of the damage are: None (N), Slight (S), Moderate (M), Extensive (E), and Complete Damage (C). Descriptions of these damage states are found in the Hazus Technical Manual (NIBS 2012). For full appreciation of the discussion of approach, methodology, and procedure used for this study, a general familiarity with the Hazus Earthquake Model is necessary; this can be obtained from several sources (NIBS 2012; Kircher et al. 2006b; Hansen et al. 2010).

The existing Hazus damage functions may be modified or new building types can be created and assigned unique damage functions. Fortunately, many of the Hazus building types have similar international counterparts. For example, the global building inventory developed for the USGS PAGER program (Jaiswal and Wald 2008), as well as the World Housing Encyclopedia (EERI and IAEE n.d.) and D'Ayala (2011) demonstrate that nonductile concrete frame (Hazus C3) and unreinforced masonry (Hazus URM) are very prevalent outside the United States, including in Venezuela. But international building types include other nonengineered structures and types such as adobe that are not specifically represented by the existing 144 options in Hazus. Accurately estimating potential damages at low levels of ground motion would require development of damage functions for highly vulnerable nonengineered structures including adobe, although the deterministic scenarios utilized in this study expose the Mérida State building stock to relatively strong ground motions.

Most of the Mérida State building stock can be assigned to engineered building types and some level of seismic design that have U.S. counterparts although additional



uncertainty is introduced. Coronel and López (2013) assessed both concrete frame and unreinforced masonry school buildings of various seismic design levels and damage states as a result of the 1997 earthquake in Cariaco in Venezuela. They found generally higher vulnerabilities for these school buildings than the Hazus fragilities, but they were similar for the complete damage category. We have focused our result reporting for our estimates on the complete damage state (buildings damaged beyond repair) and overall conclude that the impacts presented here may only be a minimum. Developing new damage functions for Mérida State require a characterization of the nonlinear pushover structural behavior of its buildings that is outside the scope of this work; however, assigning building type and design levels to Mérida State from similar U.S. counterparts provides the critical capability to perform a broad range of risk assessments with a sound loss estimation methodology outside the United States. We acknowledge, however, that significant efforts might be necessary to develop fragility curves for all Venezuelan building types.

The methodology for determining injuries and casualties is based on the strong correlation between building damage (both structural and nonstructural) and the number and severity of casualties based on the distribution of the population at different times of the day. For our study, we assessed the highly vulnerable residential building stock using nighttime maximum residential occupancy loads.

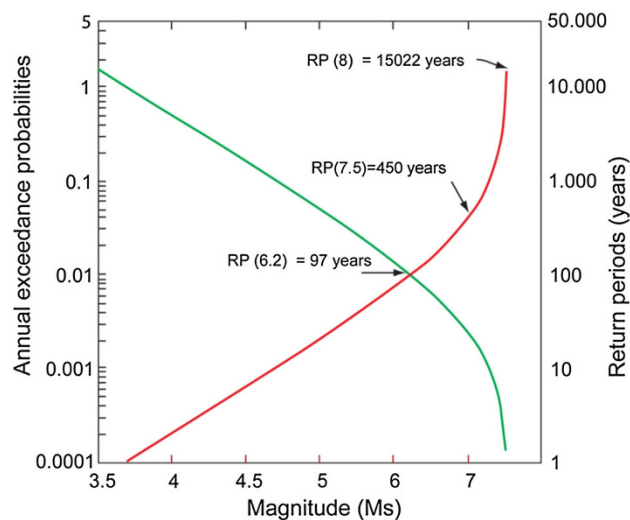
#### 4 Selection of Scenario Earthquakes

Scenario earthquakes were selected based on the potential reoccurrence of historic earthquakes that occurred in Mérida State. Our primary goal was to expose the building stock in Mérida State to ground motions associated with the return periods (475 years and 970 years) proposed in the table of Earthquake Design Levels of Vision 2000 (SEAO Vision 2000 Committee 1995), given in Table 1, and utilized in the current Venezuelan seismic design codes for buildings. This was accomplished by using the seismic recurrence and hazard curves developed for Mérida State by Bendito et al. (2001). The scenario event magnitudes ( $M$  7.5 and  $M$  7.7) were selected based on the return

frequencies shown in Fig. 3. Subsequently, we compared the peak ground acceleration (PGA) of the scenario earthquakes generated for this study within the urban tracts for Mérida State to ensure the PGAs used for loss modeling correlate with the 475 and 975 year frequencies of the seismic hazard curve for Mérida State (Fig. 4) from Bendito et al. (2001).

The region evaluated for seismic hazard comprised the western region of Venezuela, with the fault systems of Boconó, Oca-Ancón, Perijá, and the Nido of Bucaramanga in Colombia being the principal tectonic features (Fig. 1). These fault systems have historically been the cause of significant earthquakes.

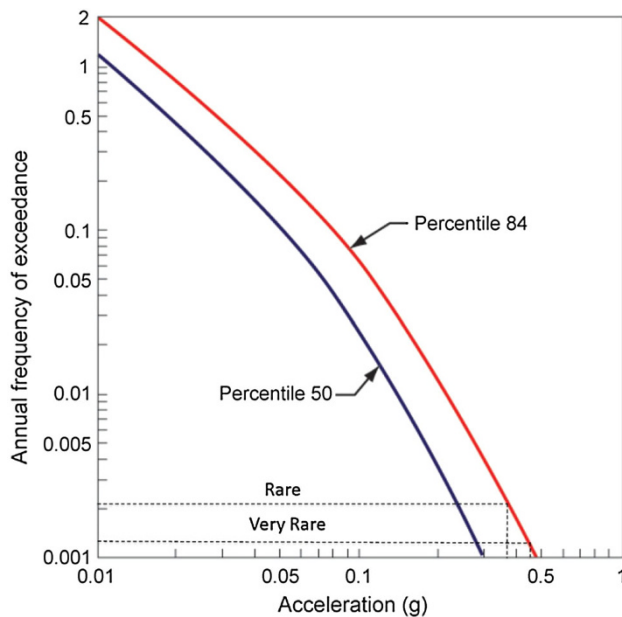
Delimiting seismic sources in western Venezuela with its different types of faults requires special attention. This is due to lack of definite information about the relationship between geology and local seismicity, to the limited accuracy of existing historical seismicity knowledge, and to the brief period of instrumental seismicity. The presence of other fault systems, inferred or hidden, could represent a secondary threat of unknown potential. One of the fourteen seismotectonic zones examined in the Bendito et al. (2001) model covers Mérida State, historically has produced large earthquakes, and is the seismotectonic zone of interest for



**Fig. 3** Seismic recurrence curve for Mérida State. Source Bendito (2001)

**Table 1** Earthquake design levels and structural performance levels according to SEAO's Vision 2000 study

Earthquake design level	Recurrence interval (years)	Annual frequency of exceedance	Probability of occurrence	Performance level
Frequent	43	0.02310	50 % in 30 years	Fully operational
Occasional	72	0.01386	50 % in 50 years	Operational
Rare	475	0.00211	10 % in 50 years	Life safe
Very rare	970	0.00105	10 % in 100 years	Near collapse



**Fig. 4** Seismic hazard curve for Mérida City. *Source* Bendito et al. (2001)

our study. These seismotectonics zones are relatively homogeneous areas from the point of view of earthquake generation potential, since it is assumed that each point inside a seismogenetic zone has the same probability of becoming the epicenter of a seismic event.

According to the curve of seismicity and return periods shown in Fig. 3, the recurrence of events of magnitude  $M$  7.5 is 450 years and for events of magnitude  $M$  6.2 is approximately 97 years. For this study we incorporate two PGA values found in Bendito et al. (2001) for Mérida State that we produce from credible PSHA for two different earthquake design levels: the rare and the very rare. This selection of seismic events is based on the potential reoccurrence of historic earthquakes that are associated with magnitudes greater than  $M$  7 and with return periods greater than 120 years.

Lack of data for strong accelerations in the region make it impossible to select attenuation relationships on the basis of local accelerographic registers. Generally, these have been defined by intensity relationships based on historical seismic data, reduced to acceleration by conversion relationships and by some attenuation relationship based on accelerographic registers of small magnitude seismic

events. Thus, for the western region of Venezuela, attenuation equations were used. These relationships were derived from accelerographic data from other areas with a similar tectonic structure, taking into account the type of faulting, the rock type, and the near fault effects.

Four attenuation relations characterizing events generated in crustal faults at small to medium depths, and one relation for subduction zone events, applicable to the Nido of Bucaramanga, in Colombia were used in the study. The relationships used in the first category were drawn from Boore et al. (1993), Campbell (1993), Sadigh et al. (1993), and Idriss (1993), while Crouse (1991) was used for the second category.

The results of the probabilistic seismic hazard model in west Venezuela were obtained using the EZ-FRISK software (Risk Engineering 1999). For any point in the region under study, the program calculates four curves of seismic hazard. The definitive hazard curves represent the mean of the four curves for the two levels of uncertainty assessed in the attenuation relationships used as determinants: one with average values ( $M$ ) and the other with average values plus one standard deviation ( $M + 1\sigma$ ) specified for each attenuation relation, according to rock conditions. Figure 4 shows the hazard curve for Mérida City. The PGA values associated with the two selected scenarios (rare and very rare) that are used for the ShakeMap are shown in Table 2. The epicenter was the epicenter of the historical large earthquake that occurred in Mérida State on 1674.

## 5 Parameters for the User-Supplied Scenario Earthquake

Hazus has the capability to produce ground motions by defining earthquake parameters, directly incorporating probabilistic ground motions, or using ground motion data provided by another source and importing the data as a “user-supplied” hazard. For this study we relied on the USGS ShakeMap products and brought it into Hazus as a user-supplied hazard. By using ShakeMap products we benefit from the inclusion of soil amplification factors and more refined fault parameters, and utilize products that will be generated following future earthquakes in Venezuela. Therefore, familiarity with ShakeMap products and the

**Table 2** Parameters for the user-supplied type of scenario earthquakes along the Boconó fault

Scenario	Return period (years)	Annual frequency of exceedance	Acceleration (g)	Magnitude ( $M$ )	Location	
					Latitude	Longitude
Rare	475	0.00211	0.37	7.5	8.84	−70.68
Very rare	970	0.00105	0.46	7.7	8.44	−70.68

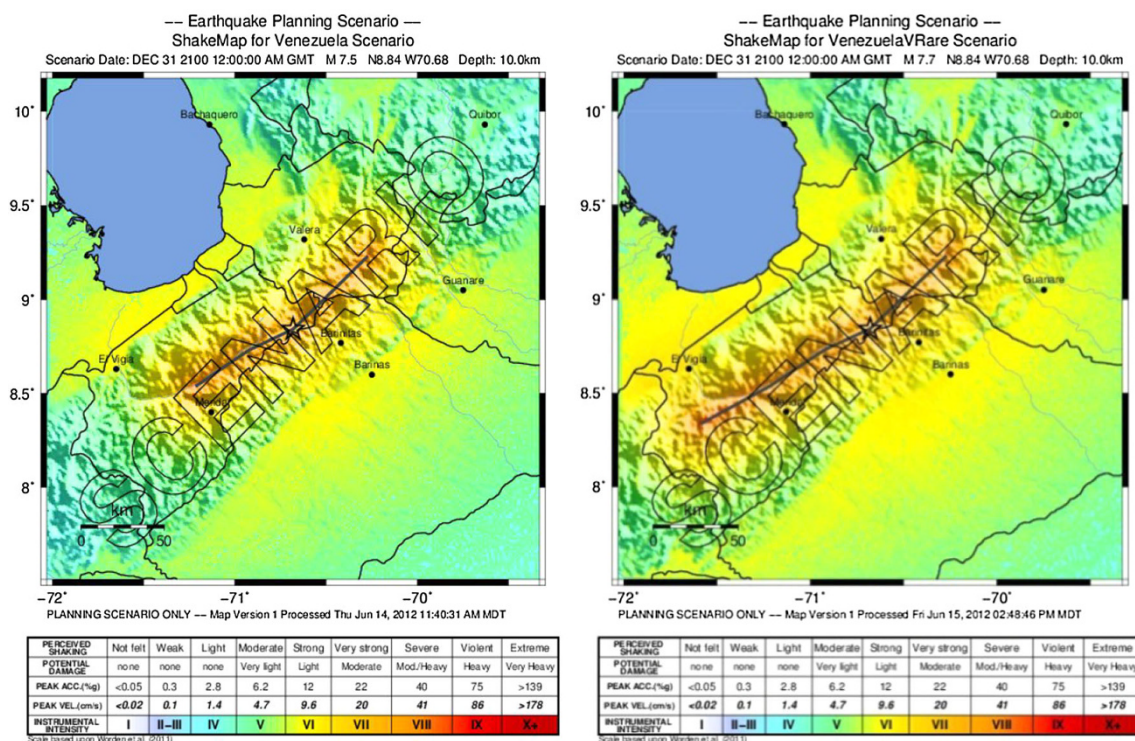
experience gained in assessing losses based on their input is valuable for Venezuela. The parameters for generating the ShakeMap ground motion products for Mérida State were selected based on the PSHA of Bendito (2001) and described in Table 2.

## 6 ShakeMap Scenario Earthquakes

A ShakeMap is a representation of ground shaking produced by an earthquake. ShakeMap information is different from the earthquake magnitude and epicenter that are reported after an earthquake because ShakeMaps provide the ground-shaking produced by the earthquake, rather than the parameters describing the earthquake source. This makes ShakeMap far more valuable in assessing the impacts associated with an earthquake. An earthquake produces a range of ground-shaking levels throughout a region depending on source, path, and site effects. ShakeMap products include separate maps of the spatial distribution of ground motions (acceleration, velocity, and spectral response) as well as a map of estimated seismic intensities. These maps provide a rapid portrayal of the extent of potentially damaging shaking following an earthquake and can be used for emergency response, loss estimation, and for public information through the media.

For potentially damaging earthquakes, ShakeMap produces response spectral acceleration values at three different periods (0.3, 1.0, and 3.0 s) for use not only in loss estimation, but also for earthquake engineering analyses. Response spectra for a given location are useful for portraying the potential effects of shaking on particular types of buildings and structures. Following a damaging earthquake, ShakeMaps of spectral response will be key for prioritizing and focusing post-earthquake occupancy and damage inspections. For the Hazus program, the ShakeMap products include a hazus.zip file containing the GIS layers that Hazus requires, including PGA, Peak Ground Velocity (PGV), and spectral accelerations at 0.3 and 1.0 s. In addition, ShakeMap modeling incorporates available strong ground motions if recorded on strong motion instrumentation or will estimate intensity using felt reports collected from the public through the internet, such as Did You Feel It? (Wald et al. 2006).

We used two USGS provided ShakeMap scenarios (Fig. 5) where the maximum PGAs correlate with the ground motions for Mérida State found on the PSHA of Bendito et al. (2001) for rare and very rare return periods depicted in Table 3 (USGS 2009). Both events are centered on the Boconó fault with a right-lateral strike-slip mechanism, an azimuth of N 45°E, and a depth of 10 km. The ShakeMap manual (Wald et al. 2006) thoroughly describes



**Fig. 5** USGS ShakeMap scenarios for Mérida State showing the instrumental intensity map for the magnitude-7.5 rare scenario (*left*) and for the magnitude-7.7 very rare scenario (*right*). By default, the

intensity map is shown, although peak ground acceleration and velocity as well as spectral response maps are easily accessed via the second row of links above the map. *Source* USGS (2009)



**Table 3** Comparison between PGA values from ShakeMap and Bendito et al. (2001) for the rare and very rare return periods with ground motions impacting the urban tracts of Mérida State

Scenario	Return period (years)	Annual frequency of exceedance	PGA (Bendito 2001)	PGA mean (ShakeMap)	Magnitude ( <i>M</i> )
Rare	475	0.00211	0.37	0.36	7.5
Very rare	970	0.00105	0.46	0.47	7.7

the methodology employed including the use of Chiou and Young (2006) representation of peak ground and spectral values, the Wald et al. (1999) relationship between Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Modified Mercalli Intensity (MMI), and Allen and Wald (2009) Intensity Prediction Equations (IPEs) to relate ground motion to intensity for the two scenarios used in this study.

## 7 Data Collection and Preparation

To generate more accurate estimates, this study collected and incorporated region and specific inventories including soil maps, liquefaction susceptibility, landslide susceptibility, demographic data, and building inventory. These parameters are discussed in more detail in the following sections.

### 7.1 Soil Condition

Venezuelan seismic design codes for buildings (COVENIN 1756:2001) divides the soil into three classes S1 (hard and dense soil) to S3 (soft and loose soil). Both Hazus and ShakeMap utilize the National Earthquake Hazard Reduction Program (NEHRP) soil types and apply an amplification factor that includes five classes, from hard rock (A) to soft rock (E). In the case of the ShakeMap scenarios used for this study, soil amplification is already included in the ground motion estimates based on predefined shear wave velocities for the upper 30 m of soil around the world (USGS 2010). The development of soil type mapping for this study was completed to evaluate the predominant soil types impacting the Mérida State building stock and did not replace the soil amplification mapping already incorporated into ShakeMap. The relationships between the NEHRP soil types used by Hazus and those from the Venezuelan Code are shown in Table 4. Although there are localized differences, our study area buildings are primarily sited on D soils where there is fairly good agreement between the NEHRP and Venezuelan Code amplification parameters.

### 7.2 Other Induced Effects

Other induced local effects such as liquefaction and landslide susceptibility are incorporated as Hazus user-supplied

**Table 4** Equivalence between soil types for Hazus format and Venezuelan Code

Soil type	Shear wave velocity (m/s)			
	Hazus (NEHRP) format		Venezuelan code	
A	1,500	NA	NA	NA
B	760	1,500	500	NA
C	360	760	250/400	500
D	180	360	170	250/400
E	NA	180	NA	170

hazard layers, using GIS maps from Castillo (2006) that considered slope, geology, and soil types. Castillo (2006) implemented the Hazus 10 landslide susceptibility categories, as well as the five liquefaction susceptibility categories into the products used for this study. Figure 6 shows the landslide susceptibility for Mérida State. The Hazus methodology estimates ground deformation based on combining susceptibility with scenario ground motions, and applies damage functions based on an estimate of permanent ground deformation, as well as a probability of ground deformation defined by using the susceptibility input (NIBS 2012, Table 4.18).

### 7.3 Demographic Data

The population totals and demographic distributions were first derived using Oak Ridge National Labs LandScan 2008 population data (ORNL 2008) and Venezuela census 2011 (INE 2011) data that were assigned to each census tract by following the procedure suggested by Hansen et al. (2010). LandScan is the finest resolution global population distribution dataset containing granular population data down to the square kilometer level. It was developed by the Oak Ridge National Laboratory (ORNL) for the US Department of Defense. The LandScan algorithm uses spatial data and imagery analysis technologies and a multivariable dasymetric modeling approach to disaggregate census counts within an administrative boundary (ORNL 2008).

The Hansen et al. (2010) procedure allows users outside the United States to utilize the Hazus program by first distributing U.S. proxy data and provides instructions on replacing these proxy data with country-specific information.

We started with the available Hazus Puerto Rico datasets and completed the replacement using an extensive building inventory for Mérida State, as well as the Venezuelan census demographic attributes to better estimate population distribution based on time of day.

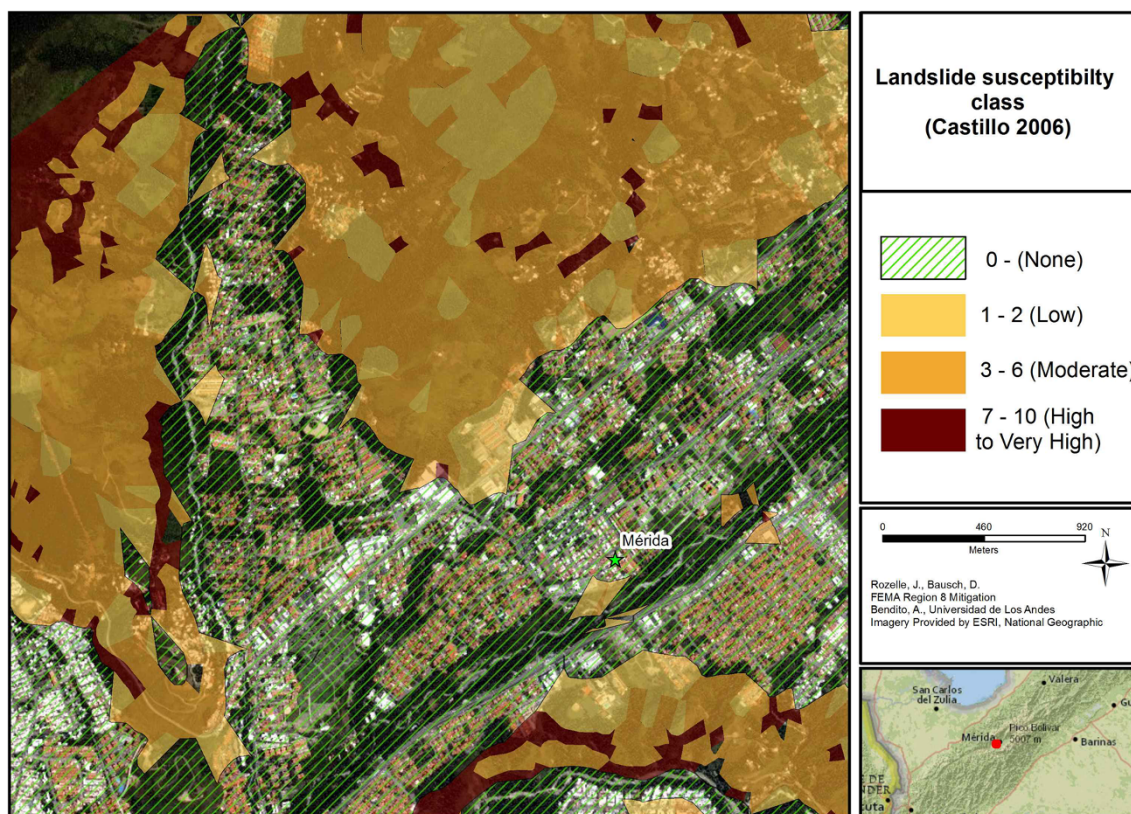
The geographical size of the detailed Mérida State study region is 5,711 square miles and contains 2,448 census tracts. For the urban area the tracts are one square kilometer and for the rural areas we used 10 square kilometer units. A flow diagram describing how this information was pulled together and applied to this study is shown in Fig. 7. Full appreciation of the approach, methodology, and limitations can be obtained from Hansen et al. (2010).

#### 7.4 Building Inventory

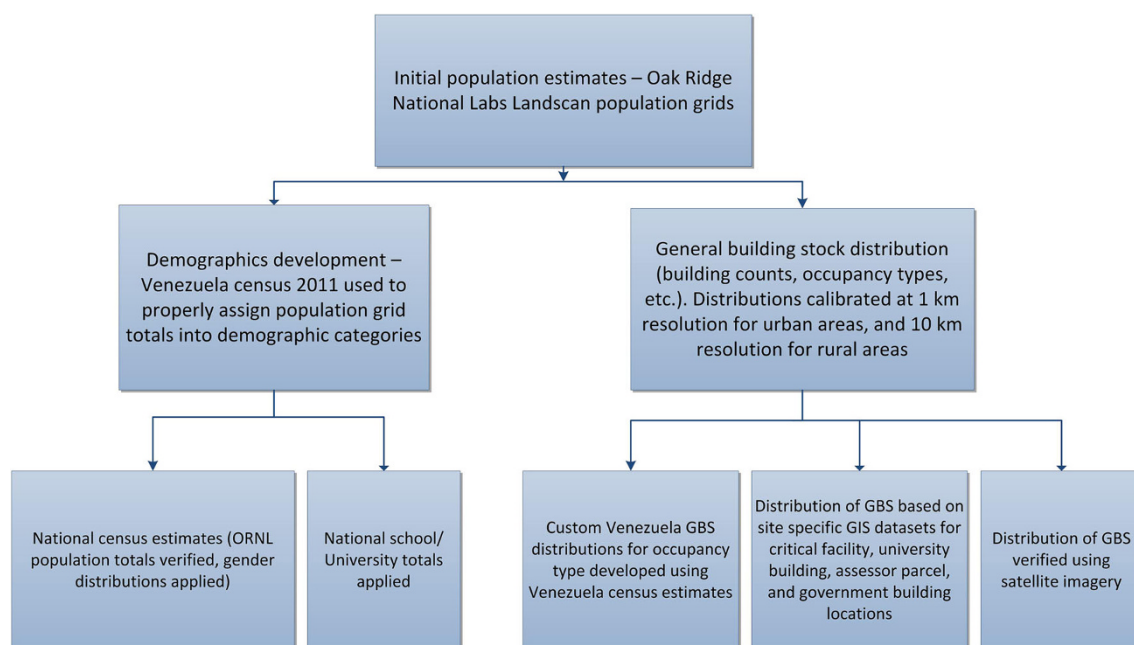
The inventory data for Mérida State include census 2011 data on population totals and demographics distribution, as well as field data from different studies conducted at the Universidad de Los Andes. These studies include an inventory of construction typologies with year built, estimated floor area, and number of stories in different areas of Mérida State from Ferrer and Laffaille (2002a, b, c, d), Castillo et al. (2008), Montilla and Castillo (2011), Suárez

and Dávila (2006), and Lira (2008). Expert knowledge from Venezuelan structural engineers was utilized to match the building types for Mérida State to Hazus building types. More local expertise was contributed by the Institute of Disaster Prevention (INPRADEM), whose staff shared their available knowledge and GIS maps on building inventories. The building inventory includes residential, commercial, industrial, agricultural, religious, government, and educational buildings. The building stock in the region consists of about 375,000 buildings. The building stock was classified according to the following types of occupancy: residential (81 % of the total number of buildings); commercial and industrial (18 %); religious, governmental, and educational (1 %).

The buildings were further aggregated into Hazus by the year built, estimated floor area, number of stories, and the seismic design level based on the year the structure was built. Over the period from 1939 to the present, seismic provisions of building codes have evolved. We utilized three building code levels for the Mérida State building stock based on the benchmark years of seismic building code adoption in Venezuela. We assigned Pre-Code (PC) to buildings built prior to 1967 (which represents 35 % of the total buildings). Low-Code (LC) was assigned for the years 1967 to 1998 based on the adoption of the Venezuelan



**Fig. 6** Landslide susceptibility for Mérida State. *Source* Castillo (2006)



**Fig. 7** Demographic and general building stock development methodology

seismic design codes for buildings COVENIN 1756:1998, *Edificaciones Sismorresistentes* (which represents 53 % of the total buildings), and Moderate-Code (MC) was assigned to buildings built after 2001 when the current Venezuelan seismic design code for buildings (COVENIN 1756:2001, *Edificaciones Sismorresistentes*) was adopted (which represents 12 % of the total buildings).

We also collected detailed information for essential facilities. For example, the University Hospital (Hospital type IV), key government buildings, theaters, and airports were also included in Hazus. The damage state probability of the general building stock is computed based on the spectral ground motions at the centroid of the census tract. Since there are no specific damage functions available for Mérida State, the present study used functions provided by Hazus that are similar to the Mérida State building types and seismic design levels.

## 8 Results and Discussion

Use of scenario earthquakes presents one possible outcome associated with the events modeled for this study. An accurate performance of a particular loss estimation scenario depends on many variables, which include the presence or absence of irregularities in height, the level of structural redundancy, differences in the height between adjacent buildings, the disposition of nonstructural elements, the accuracy of the structural calculus, the relative fulfillment of structural detail, the level of inspection and control of construction, and even the degree of existing maintenance. But

**Table 5** Expected building damaged

Scenario	Magnitude	% Buildings at least moderately damaged	% Buildings damaged beyond repair
Rare	7.5	47	16
Very rare	7.7	61	18

we believe that as a result of the significant size of our Mérida State building inventory (375,029) the potential variability is minimized and the aggregated results represent the major aspects of seismic risk for Mérida State. In addition, presenting much of the results in terms of damage percentages and loss ratios relative to occupancy categories further help address uncertainties that may be reflected in total damages.

Table 5 summarizes the percentage of the expected building damaged for each scenario. For example Hazus estimates that about 142,880 buildings will be at least moderately damaged (damage is expressed as the probability that a given building will realize at least moderate damage) for the rare scenario. This is over 47 % of the buildings in the region. There are an estimated 48,640 buildings that will be damaged beyond repair. This is over 16 % of the buildings in the region.

Descriptions of these damage states are provided in Volume 1: Chapter 5 of the Hazus technical manual (NIBS 2012). This high rate of moderate damage (47 and 61 %, depending on the scenario) demonstrates the high



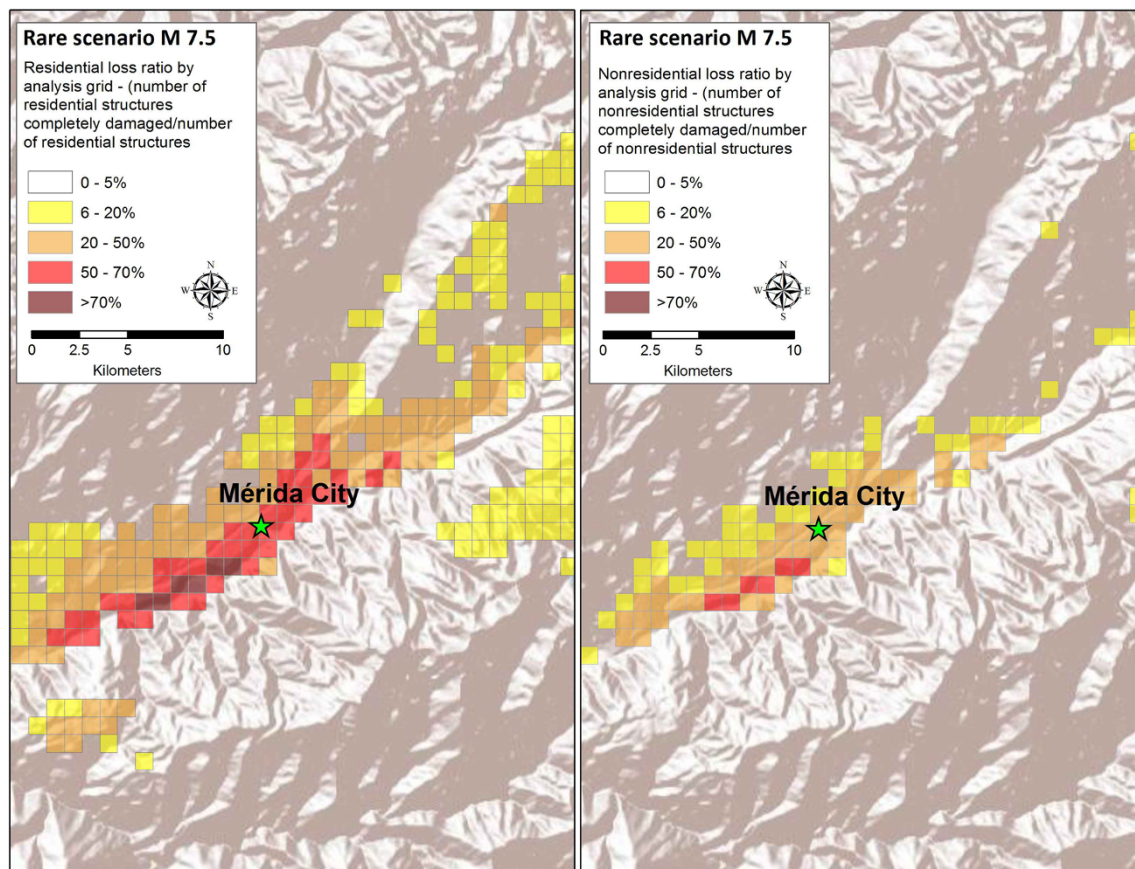
**Table 6** Expected earthquake building damage by occupancy and by building type (% loss ratio)

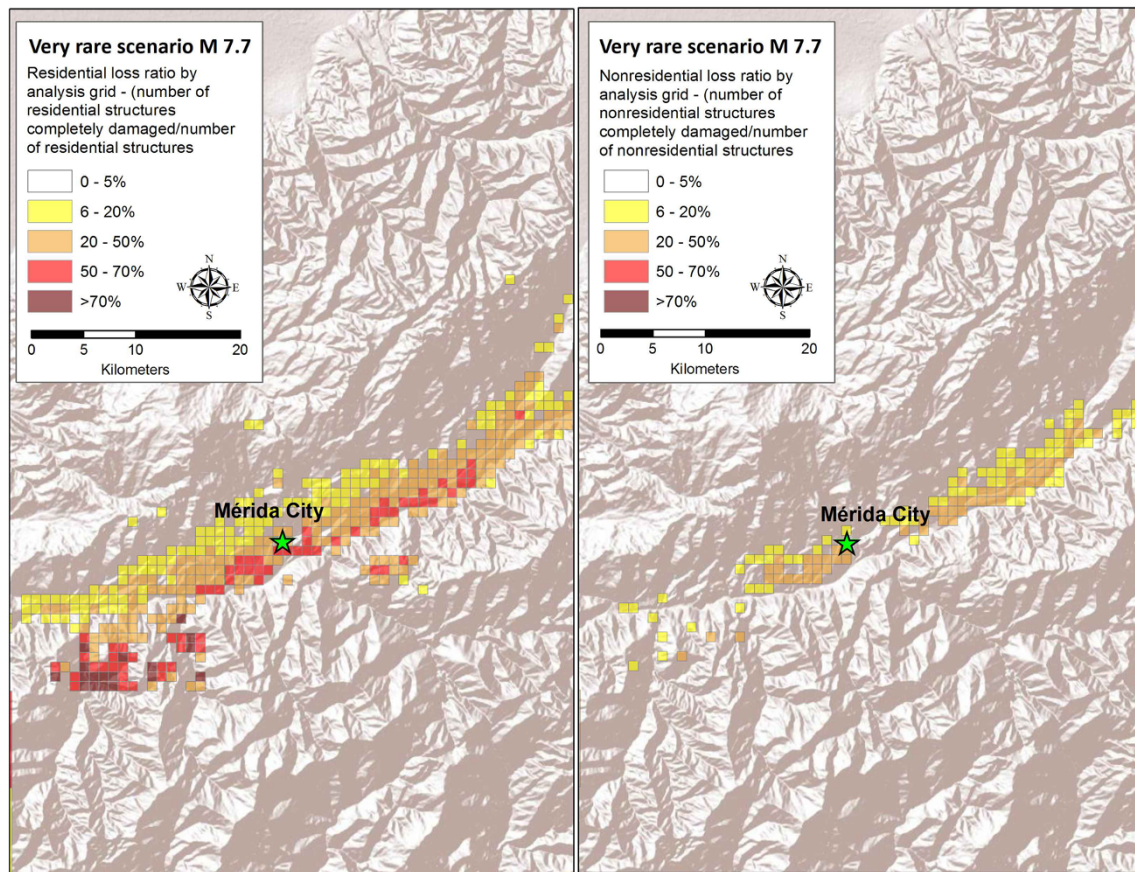
	Total counts	Earthquake scenario			
		Rare		Very rare	
		Buildings damaged beyond repair			
		Counts	% Loss ratio	Counts	% Loss ratio
<i>Building occupancy</i>					
Agriculture	702	91	13	84	12
Commercial	55,050	5,448	10	5,082	9
Education	1,400	129	9	116	8
Government	733	25	3	33	4
Industrial	9,432	1,074	11	964	10
Religion	2,021	1,954	10	251	12
Residential	305,689	43,141	14	45,847	15
<i>Building type</i>					
Steel	21,700	2,386	11	2,138	10
Concrete	131,832	1,672	13	16,870	13
Precast	5,417	335	6	307	5
URM	216,078	32,686	15	33,063	15

vulnerability of most of the region's buildings. In Table 6 we discriminate the damage by counts of occupancy and by building type. We also present the loss ratios, which are the counts of buildings classified as completely damaged divided by the total building counts in each category.

The majority of damage will occur to residential structures, which are predominately Unreinforced Masonry construction (URM), followed by concrete building types (Concrete Moment Frame (C1), Concrete Shear Walls (C2), Precast Concrete Frames with Concrete Shear Walls (PC2)). In Mérida State 70 % of the residential building stock are built of URM and 30 % of concrete. Figures 8 and 9 present the residential and nonresidential loss ratio for the rare and very rare scenario, respectively, demonstrating higher loss ratios for residential occupancy types.

In Mérida State 95 % of the residential buildings have heights between 1 and 3 stories and the predominant fundamental period of the soil in some parts of the city range between 0.2 and 0.4 s. The residential buildings on this soil class perform very poorly or deficiently in each event because they have the potential to vibrate with the same harmonic frequency as the ground on which they sit.

**Fig. 8** Residential (*left*) and nonresidential (*right*) loss ratio in Mérida State for the rare scenario



**Fig. 9** Residential (*left*) and nonresidential (*right*) loss ratio in Mérida State for the very rare scenario

**Table 7** Elastic spectra acceleration values with 5 % damped response spectrum for the horizontal components for the two scenarios obtained with ShakeMap scenario and the Venezuelan standard for seismic regulations values for the residential buildings in Mérida State (seismic zone 5)

Scenario	ShakeMap scenario acceleration (g) values		Venezuelan code acceleration (g) values (Seismic zone 5)	
	Max 0.3 s	Max 1 s	Max 0.3 s	Max 1 s
Rare	1.42	0.70	0.86	0.60
Very rare	1.54	0.92	1.07	0.75

We can also observe in Table 7 that the ShakeMap scenario spectral accelerations for Mérida State are exceeding the code acceleration values on the 0.3 s period (similar period of 95 % of the residential buildings) for the two scenarios. These results further help identify the relatively higher vulnerability for the residential building stock and the requirement to develop mitigation strategies to reduce their seismic vulnerability. In addition, based on the building capacity-spectral ground motion methodology of Hazus (NIBS 2012), spectral ground motions are a much larger driver of building losses in Hazus than PGA alone.

**Table 8** Estimates of the number of displaced households for each scenario for Mérida State

Total number households	Rare (M 7.5)		Very rare (M 7.7)	
	Displaced	%	Displaced	%
269,738	44,143	16.4	45,951	17

Table 8 estimates the number of displaced households, which are a function of the number of residences with extensive or complete structural damage. People from displaced households will seek and require alternative shelter. The corresponding estimates of the number of people seeking public shelter are 44,143 for the rare scenario and 45,951 for the very rare scenario. We hope these results will help the state and city governments of Mérida, Venezuela to prepare proper disaster management strategies at the initial planning level.

Table 9 distributes estimates of severe casualties (life-threatening and fatalities) at nighttime for each Model Building Type (MBT). Casualties are based on M7.7 ground motions. Table 9 also shows the corresponding fraction of all fatalities for each MBT, the MBT square

**Table 9** Distribution of estimated nighttime (2 a.m.) severe casualties due to M 7.7 ground motions (very rare scenario) by model building type

Model building type (MBT) label	Seismic design level	Relative MBT use			Buildings completely damaged	Casualties at 2 a.m.			Relative risk factor
		Total number of buildings	Area (SF $\times 10^3$ )	% of total		Life Threatening	Fatalities	% of total	
C1	LC/MC	41,699	67,707	12.26	1,964	33	66	3	0.23
C2	LC/MC	10,851	17,354	3.14	246	1	2	0	0.03
C3	LC/MC	16,328	27,079	4.90	1,192	320	636	27	1.30
C3	PC	62,956	89,395	16.19	13,324				
PC2	LC/MC	5,417	9,769	1.77	306	7	14	1	0.34
S5	LC/MC	21,700	29,722	5.38	2,137	3	5	0	0.04
URM	PC	216,078	311,257	56.36	33,063	809	1,596	69	1.22
All buildings		375,029	552,283		52,232	1,173	2,319		

footage (SF), and the corresponding fraction of total building square footage for each MBT. Finally, using a methodology from Kircher et al. (2006a) a “relative risk” factor is calculated as the ratio of the fraction of severe casualties divided by the fraction of total square footage for each MBT. Values greater than 1.0 imply above-average life safety risk compared to other MBT. This highlights the significant relative risk associated with Mérida’s Concrete Frame with Unreinforced Masonry Infill Walls (C3) and Unreinforced Masonry Bearing Wall (URM) construction.

For the other Model Building Types, namely, Concrete Moment Frame (C1), Concrete Shear Walls (C2), Precast Concrete Frames with Concrete Shear Walls (PC2), and for the Steel Frame with Unreinforced Masonry Infill Walls (S5) the relative risk factor is below 1.

This study estimates that for the M 7.7 ground motions occurring at night, more than 2,300 people will be killed, and almost 46,000 households will be displaced.

## 9 Conclusions

An important objective of this study is to highlight that another large earthquake is a potential reality in Mérida State at any time; the day this may occur cannot be predicted, but future impacts are likely to have a more severe affects than the last large earthquake on 28 April 1894. There should be no hesitation to prepare proper preplanned mitigation activities; one step forward is assessing seismic loss potential from scenario earthquakes completed in this study in urban and rural areas for Mérida State in Venezuela using Hazus. This has been possible because of the significant amount of information available about the seismic hazard of the state and the typology, age, and other characteristics of the building stock of Mérida State.

Although we have shown that Hazus is a useful loss estimation methodology there are several necessary steps required to improve the existing Hazus methods for

Venezuela. These include: (1) developing capacity and fragility curves directly for Venezuelan building types, in accordance with the Hazus platform demands; (2) extending these methods to a multi-hazard assessment, for example including floods; (3) collecting and inputting more detailed data for essential facilities such as hospitals, schools, electric power stations, pumping stations, water, gas, electricity, communications, hazardous-material facilities, and so on.

The findings of this study are based on an important assumption: the seismic vulnerability and fragility relationships embedded in Hazus for unreinforced masonry and for the nonductile concrete frame buildings are truly representative of building types in Mérida State of Venezuela. The hazard data, including the ShakeMap ground motion products, as well as the landslide and liquefaction susceptibility maps, are additional sources of uncertainty.

Mérida State currently has a high seismic risk because of its significant exposure, the concentration of buildings, and the fragility of their structures. Residential buildings would be the most severely impacted and drive the majority of the potential loss of life and property in future earthquakes. For the very rare scenario, for instance, one of many possible scenario iterations resulted in 85 % of the buildings suffering at least moderate damage.

The adoption and enforcement of an adequate building code is one of the most effective loss prevention measures that a state or community can implement. The difference in building performance was contrasted dramatically in two recent events: the earthquake in Haiti on 12 January 2010, where over 220,000 people lost their lives and more than 300,000 were injured (EERI 2010). This earthquake released nearly 1,000 times less energy than the earthquake in Chile that occurred 30 days later and that also affected a densely populated zone with a balance of 1,000 less victims. Building standards and codes specific for Haiti do not exist (Ove Arup & Partners 2010).

Our study can serve as a reference to complement the seismic hazard map in the Venezuelan code, with different



limit performance states that will permit the application of seismic performance level engineering in Venezuela. A proper preplanned mitigation activity not only can save human lives but can also reduce the potential social and economic effect of disasters. By expressing potential earthquake impacts in terms of potential loss of life and property through Hazus loss modeling, we believe the study will enable the state and city governments of Mérida, Venezuela to prepare proper disaster management strategy at the initial planning level. This preparation would reduce the potential impact of a future seismic disaster. Loss estimates are a key tool in prioritizing the allocation of limited resources, as well as preventing cascading events that can exacerbate the initial effects of a disaster.

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## References

- Allen, T.I., and D.J. Wald. 2009. Evaluation of ground-motion modeling techniques for use in Global ShakeMap: A critique of instrumental ground-motion prediction equations, peak ground motion to macroseismic intensity conversions, and macroseismic intensity predictions in different tectonic settings. U.S. Geological Survey Open-File Report 2009-1047 114. Golden, CO: USGS.
- Bendito, A. 2001. Analysis of seismicity and isoacceleration curves for structural performance levels in western Venezuela (*Análisis de sismicidad y curvas de isoaceleración para estados de desempeño estructural en el Occidente venezolano*). Master's thesis in Structural Engineering, Faculty of Engineering, Universidad de Los Andes, Mérida, Venezuela (in Spanish).
- Bendito, A., P. Rivero, and W. Lobo-Quintero. 2001. Isoacceleration curves for structural performance levels in western Venezuela (*Curvas de Isoaceleración para Estados de Desempeño Estructural en el Occidente de Venezuela*) vol. 39, no. 2: 1–18. Caracas, Venezuela: Boletín Técnico del Instituto de Materiales y Modelos Estructurales (IMME) (in Spanish).
- Boore, D.M., W.B. Joyner, and T.E. Fumal. 1993. Estimation of response and peak accelerations from western North American earthquakes. U.S. Geological Survey. Open File Report 93-509. EZ-FRISK™ Attenuation Equation References. Merlo Park, CA: USGS.
- Buika, J.A. 2000. A public–private partnership to develop the HAZUS earthquake risk assessment capabilities for the San Francisco Bay Area, California. A paper report in the Federal Emergency Management Agency (FEMA), Mitigation Division. San Francisco, CA: FEMA.
- Campbell, K.W. 1993. Empirical prediction of near source ground motion from large earthquakes. *Proceedings, international workshop on earthquake hazard and large dams in the Himalaya*, sponsored by the Indian National Trust for Art and Cultural Heritage (INTACH), January 15–16, 1993, in New Delhi, India.
- Castillo, A. 2006. Seismic risk scenarios for buildings in Mérida, Venezuela. Detailed vulnerability assessment for non-engineered housing. Doctoral diss., Technical University of Catalonia, Barcelona.
- Castillo, A., F. López-Almansa, and L.G. Pujares. 2008. Seismic risk reduction measures of a vulnerable urban informal settlement in Mérida, Venezuela. Cost-benefit analysis. The 14th world conference on earthquake engineering, Beijing, China.
- Chock, G., I. Robertson, P. Nicholson, H. Brandes, E. Medley, P. Okubo, T. Kindred, G. Inuma, E. Lau, A. Sarwar, J.D. Pino, and W. Holmes. 2006. Compilation of observations of the October 15, 2006 Kiholo Bay (Mw 6.7) and Mahukona (Mw 6.0) Earthquakes, Hawaii. Report for the Earthquake Engineering Research Institute and the Structural Engineers Association of Hawaii, Hawaii.
- Chiou, B., and R. Young. 2006. PEER-NGA empirical ground motion model for the average horizontal component of peak acceleration and psuedo-spectral acceleration for spectral periods of 0.01 to 10 seconds. Pacific Earthquake Engineering interim report for USGS review.
- Coronel, G., and O.A. López. 2013. Methodology for estimating earthquake injuries in school buildings in Venezuela by fragility curves (*Metodología para la Estimación de Daños Por Sismos en Edificios Escolares de Venezuela Mediante Curvas de Fragilidad*). *Revista de la Facultad de Ingeniería-UCV* 28(2) (in Spanish).
- COVENIN (Comisión Venezolana de Normas Industriales). 1998. COVENIN 1756:1998, Venezuelan seismic design codes for buildings (COVENIN 1756:1998, *Edificaciones sismorresistentes*). Caracas, Venezuela: Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS) (in Spanish).
- COVENIN (Comisión Venezolana de Normas Industriales). 2001. COVENIN 1756:2001, Venezuelan seismic design codes for buildings. Requirements (COVENIN 1756:2001, *Edificaciones sismorresistentes. Requisitos*). Caracas, Venezuela: Fondonorma (in Spanish).
- Crouse, C.B. 1991. Ground-motion attenuation equations for earthquakes on the Cascadia subduction zone. *Earthquake Spectra* 7(2): 201–236.
- D'Ayala, D. 2011. Unreinforced brick masonry construction. University of Bath, United Kingdom. [http://www.world-housing.net/wp-content/uploads/2011/08/Type\\_Brick.pdf](http://www.world-housing.net/wp-content/uploads/2011/08/Type_Brick.pdf). Accessed 30 Aug 2014.
- EERI (Earthquake Engineering Research Institute). 2010. Special earthquake report. Learning from earthquakes. The Mw 7.0 Haiti Earthquake of January 12, 2010: Report #2. EERI.
- EERI (Earthquake Engineering Research Institute) and IAEE (International Association for Earthquake Engineering). n.d. World Housing Encyclopedia. <http://www.world-housing.net>. Accessed 17 June 2010.
- Ferrer, C., and J. Laffaille. 2002a. Evaluation of the physical conditions and vulnerability analysis as a basis to establish susceptibility levels of Los Pepos, Santa Cruz de Mora, Mérida (*Evaluación de las condiciones físicas y análisis de la vulnerabilidad como base al establecimiento de niveles de susceptibilidad del sector Los Pepos, Santa Cruz de Mora, Mérida*). Technical report. Mérida, Venezuela: Fundación para la

- Prevención de los Riesgos Sísmicos del estado Mérida (FUN-DAPRIS) (in Spanish).
- Ferrer, C., and J. Laffaille. 2002b. Evaluation of the physical conditions and vulnerability analysis as a basis to establish susceptibility levels of La Vega Hospital, Libertador Municipality, Mérida (*Evaluación de las condiciones físicas y análisis de la vulnerabilidad como base al establecimiento de niveles de susceptibilidad del sector La Vega del Hospital, municipio Libertador, Mérida*). Technical report. Mérida, Venezuela: Fundación para la Prevención de los Riesgos Sísmicos (FUN-DAPRIS) (in Spanish).
- Ferrer, C., and J. Laffaille. 2002c. Analysis of physical and vulnerability conditions for rehabilitation of San Jose of the Flores neighborhood (*Análisis de las condiciones físicas y vulnerabilidad con fines de rehabilitación del barrio San José de las Flores*). Technical report. Mérida, Venezuela: Fundación para la Prevención de los Riesgos Sísmicos del estado Mérida (FUN-DAPRIS) (in Spanish).
- Ferrer, C., and J. Laffaille. 2002d. A microzonification test for enabling neighborhoods in the Venezuelan Andes. III Symposium on seismic microzonation: Path to reduced vulnerability (*Un ensayo de microzonificación para la habilitación de barrios en los Andes venezolanos. III Coloquio sobre Microzonificación Sísmica: camino hacia una menor vulnerabilidad*). Technical series No. 1-2002, 37–39. Mérida, Venezuela: Fundación Venezolana de Investigaciones Sismológicas (FUNVISIS) (in Spanish).
- GSHAP (Global Seismic Hazard Assessment Program). 1999. <http://www.seismo.ethz.ch/static/GSHAP/>. Accessed 30 Aug 2014.
- Gulati, B. 2006. Earthquake risk assessment of buildings: Applicability of HAZUS in Dehradun, India. Published master's thesis in International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands.
- Hansen, R., D. Bausch, J. Rozelle, and S. McNabb. 2010. An updated GIS-based methodology for exporting the Hazus earthquake model for global applications: HAZ EM (extended Mediterranean) loss estimation. [http://www.unesco.org/science/doc/earthquake/RELEMR2010\\_Short\\_Description\\_Agenda.pdf](http://www.unesco.org/science/doc/earthquake/RELEMR2010_Short_Description_Agenda.pdf).
- Idriss, I.M. 1993. Procedures for selecting earthquakes ground motion at rock sites. National Institute of Standards and Technology, NIST GCR 93-625.
- INE (National Institute of Statistics (*Instituto Nacional de Estadística*)), República Bolivariana de Venezuela. 2011. <http://www.ine.gob.ve>. Accessed 26 Mar 2012 (in Spanish).
- Jaiswal, K., and D.J. Wald. 2008. Creating a global residential building inventory for earthquake loss assessment and risk management. U.S.G.S. Open File Report, OF 2008-1160. <http://pubs.usgs.gov/of/2008/1160/>.
- Kircher, C.A. 2003. Near-real-time loss estimation using HAZUS and ShakeMap. *Proceedings of SMIP03 seminar on utilization of strong-motion data*, 59–66. Oakland, CA, 22 May 2003.
- Kircher, C.A., H.A. Seligson, J. Bouabid, and G.C. Morrow. 2006a. When the big one strikes again—Estimated losses due to a repeat of the 1906 San Francisco Earthquake. *Earthquake Spectra* 22(S2): S297–S339.
- Kircher, C.A., R.V. Whitman, and W.T. Holmes. 2006b. HAZUS earthquake loss estimation methods. *Natural Hazards Review* 7(2): 45–59.
- Korkmaz, K.A. 2009. Earthquake disaster risk assessment and evaluation for Turkey. *Environmental Geology* 57(2): 307–320.
- Laffaille, J., F. Audemard, and M. Alvarado. 2010. San Antonio de Mucúño, Mérida Andes, Venezuela: Relocation of a doctrine town following the 1674 earthquake. The Geological Society of America Special Paper 471.
- Levi, T., D. Bausch, O. Katz, J. Rozelle, and A. Salamon. 2014. Insights from Hazus loss estimations in Israel for Dead Sea Transform earthquakes. *Natural Hazards*. doi:10.1007/s11069-014-1325-y.
- Lira, L. 2008. Estimating a scenario earthquake damage in Domingo Peña Parish, Libertador Municipality of the City of Mérida (*Estimación de un Escenario de Daños por Terremotos en la Parroquia Domingo Peña, Municipio Libertador de la Ciudad de Mérida*). Degree work submitted as partial requirement for obtaining a civil engineering degree from the Faculty of Engineering, Universidad de Los Andes, Mérida, Venezuela (in Spanish).
- Montilla, P., and A. Castillo. 2011. Seismic vulnerability of population centers. Case study: Pan de Azúcar neighborhood, Mérida, estado Mérida, Venezuela. *Revista Geográfica Venezuela* 10 (October).
- NIBS (National Institute of Building Science). 2012. *HAZUS<sup>MH</sup> technical manual*. Washington, DC: Federal Emergency Management Agency (FEMA).
- Nastev, M. 2013. *Adapting Hazus for seismic risk assessment in Canada*. Québec, Canada: Geological Survey of Canada, Natural Resources Canada.
- ORNL (Oak Ridge National Laboratory). 2008. LandScan Documentation. [http://web.ornl.gov/sci/landscan/landscan\\_documentation.shtml](http://web.ornl.gov/sci/landscan/landscan_documentation.shtml). Accessed 30 Mar 2011.
- Ove Arup & Partners. 2010. *Haiti earthquake response*. Oxfam GB. Arup Assignment Report, Job number 212323-00. London: Ove Arup & Partners Ltd.
- Ploeger, S.K., G.M. Atkinson, and C. Samson. 2010. Applying the HAZUS-MH software tool to assess seismic risk in downtown Ottawa, Canada. *Natural Hazards* 53(1): 1–20.
- Rein, A., and R.B. Corotis. 2013. An overview approach to seismic awareness for a “quiescent” region. *Natural Hazards* 67(2): 335–363.
- Remo, J.W.F., and N. Pinter. 2012. Hazus-MH earthquake modeling in the central USA. *Natural Hazards* 63(2): 1055–1081.
- Risk Engineering. 1999. *EZ-FRISK version 5.x. Computer package for seismic hazard analysis, spectral matching, and site response analysis*. Boulder, CO: Risk Engineering.
- Rod, E. 1956. Earthquakes of Venezuela related to strike slip faults? *American Association of Petroleum Geologists Bulletin* 40: 2509–2512.
- Sadigh, K., C. Chang, and N. Abrahamson. 1993. Specification of long-period ground motion. Updated attenuation relationships for rock site conditions and adjustment factors for near-fault effects. *Proceedings of seminar on seismic isolation, passive energy, dissipation, and active control*, vol. 1, 59–70. Applied Technology Council ATC-M-1.
- SEAO (Structural Engineers Association of California) Vision 2000 Committee. 1995. Performance-based seismic engineering. Report prepared by Structural Engineers Association of California. Sacramento, CA.
- Suárez, L., and N. Dávila. 2006. Qualitative estimation of the seismic vulnerability of school buildings in the city of Mérida (*Estimación Cualitativa de la Vulnerabilidad Sísmica de Edificaciones Escolares en la Ciudad de Mérida*). Degree work submitted as partial requirement for obtaining civil engineering degree from the Faculty of Engineering, Universidad de Los Andes, Mérida, Venezuela (in Spanish).
- Tantala, M., G. Nordenson, G. Deodatis, and K. Jacob. 2008. Earthquake loss estimation for the New York City Metropolitan Region. *Soil Dynamics and Earthquake Engineering* 28(10–11): 812–835.
- USGS (U.S. Geological Survey). 2009. Shakemap usVenezuela\_se. [http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/Venezuela\\_se/](http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/Venezuela_se/). Accessed 7 Feb 2010.
- USGS (U.S. Geological Survey). 2010. Predefined Vs30 Mapping. <http://earthquake.usgs.gov/hazards/apps/vs30/predefined.php>. Accessed 27 Aug 2009.

- Wald, D.J., V. Quitoriano, T.H. Heaton, and H. Kanamori. 1999. Relationship between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California. *Earthquake Spectra* 15(3): 557–564.
- Wald, D.J., C.B. Worden, V. Quitoriano, and K.L. Pankow. 2006. ShakeMap<sup>®</sup> manual, technical manual, users guide, and software guide. <http://pubs.usgs.gov/tm/2005/12A01/pdf/508TM12-A1.pdf>. Accessed 19 June 2006.
- Wong, I. 2010. Development of urban earthquake hazard maps in the United States. China/USA symposium for the advancement of earthquake sciences and hazard mitigation practices, October 19, 2010, in Beijing, China.